Recd. 12 OCT 1953

At the time of issue this report has not been published. Any author desiring to quote this paper should refer to it as "A paper of the Meteorological Research Committee (London), M.R.P. No. 822 by Mr. R.J. Murgatroyd A copy is available in the Library of the Meteorological Office."

M.R.P. 822.

S.C.I./79.

16th June, 1953.

AIR MINISTRY

METEOROLOGICAL RESEARCH COMMITTEE

A Report on the Determinations of the Speed Correction Coefficients of Aircraft Thermometers made by M.R.F. in 1951

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Summary

In Part I recent flight determinations of the speed correction coefficients of three flat plate and two conical head aircraft thermometers are described. The experiments were made at 5000 and 21000 feet with indicated airspeeds of 120 and 180 knots. No consistent variation of these coefficients with altitude was found.

The technique of these experiments is discussed in Part II. It is considered that the scatter of individual results in this work will invalidate attempts with the present aircraft available to improve substantially the accuracy of temperature measurement in aircraft.

Part I. Recent Measurements of Speed Correction Coefficients

Introduction

Flight determinations by the Meteorological Research Flight of the speed correction coefficients of the M.O. flat plate resistance thermometer and the R.A.E. pitot head resistance thermometer were reported in M.R.P. No. 527 (1) where it was stated that in both cases these coefficients decrease with increasing height.

The possible causes for this were examined in M.R.P. No. 677 (1) and it was concluded there that in the case of the flat plate thermometer this variation was probably due to a change of the position of transition from laminar to turbulent flow on the thermometer surface. A larger proportion of laminar flow would lead to a lower speed correction coefficient so that if the flow is more laminar at higher altitudes the above variation would be explained.

An attempt was made to verify this idea by flight determinations in a Hastings aircraft using the following thermometers:-

1. A standard M.O. flat plate thermometer.

2. A flat plate thermometer with two trip wires arranged ahead of the element to ensure that it was always in their turbulent wake.

3. Another flat thermometer with suction slots connected to a Venturi tube arranged as far as possible to ensure that the element was always in a laminar flow.

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4. A Sangamo-Weston conical head thermometer.

5. A Meteorological Office experimental conical head thermometer.

The use of conical head thermometers was also suggested in M.R.P. No. 677.

Flight procedure

The thermometers were mounted at various points under the nose of the Hastings aircraft and connected to M.O. thermometer bridges. Three or four thermometers were read simultaneously every ten seconds on each run together with height and airspeed. Twenty such readings were taken at the 180 knots airspeed, and thirty at the 120 knots airspeed to ensure an equal distance of air traversed on each run. Runs were made alternatively in reciprocal directions between two air positions in the order 120 knot run, 180 knot reciprocal run, 180 knot run, 120 knot reciprocal run. The averages of the 180 and 120 knot legs were then used in the subsequent calculations. Usually three or four of these series would be flown in succession, the overlapping 180, 120, 120, 180 knot runs also being used as a sequence to calculate a speed correction coefficient. Determinations were made at two levels, 5000 feet and 21000 feet. In the calculations corrections were applied for calibration compressibility errors but not position errors. The reasons for this are given in Part II of this report.

The flights were divided into two series, the M.O. flat plate thermometer being used in both series. The trip wire was added to the second flat plate thermometer between Series 1 and Series 2.

The results of the calculations are given in Table II.

Summary of results

The principal results are as follows:-

1. In the first series the M.O. flat plate speed correction coefficient decreased from 1.73 to 1.71 between 5000 and 21000 feet.

   The corresponding decrease in the second series was 1.66 to 1.62.

   It is not known why there was a decrease from 1.73 to 1.66 between the two series as the apparatus was not changed in any way.

   The speed coefficient of the second flat plate in Series 1 increased from 1.50 to 1.60 over this height range.

2. The speed coefficient of the flat plate with trip wires decreased from 1.16 to 1.14 and that of the slotted flat plate increased from 1.59 to 1.60.

3. The speed coefficient of the two conical head thermometers increased with height, the Sangamo-Weston instrument from 1.69 to 1.74 and the M.O. instrument from 1.83 to 1.87.

4. The standard deviation of individual measurements was high, the greatest being 0.16 and the smallest 0.04. The range between smallest and greatest single measurements varied between about 0.6 and 0.2. In each case the scatter at 5000 feet was considerably greater than that at 21000 feet.

/Discussion

Comments on Mr. Murgatroyd's paper on Speed Correction Coefficient.

The purpose of the suction slots in the flat plate was to prevent the boundary layer from becoming detached behind the leading edge which, rather than progressive transition, is what happens with narrow section aerofoils such as the flat plate thermometer.

The conical head thermometer was one of the first we made and was not aerodynamically "clean". Some of the faults apparent in this original design have been eliminated in later models.

The Sangamo-Weston thermometer is not, strictly speaking, a conical-head thermometer as the sensitive element is situated back from the tip in the parallel-walled section of the tube: it is, in fact, really a "flat-plate" thermometer.

The changes in boundary layer flow depend on the Reynolds number so that only if the Reynolds number changes can it be hoped to find a variation due to transition in the boundary layer. However, in the tests described, the effect of flying at the same indicated airspeed at different levels has the effect of maintaining the Reynolds number almost constant as shown below

Height (ft.)	$\sqrt{\frac{\rho_o}{\rho}}$ (ICAN)	$\frac{1}{\nu}$ (Table 1 MRP.677)	Re (for unit length) $\frac{V_i}{\nu}\sqrt{\frac{\rho_o}{\rho}}$
5,000	1.08	6	6.48 V_i
21,000	1.39	4	5.56 V_i

The changes in boundary layer flow are expected from MRP 744 to take place between about Re = 10^5 and Re = 2.2 10^5 (representative length 2 cm). Taking a mean value of V_i = 150 kts. the values of Re above come out as approx. Re = 10^5. In the circumstances therefore it is not expected that the tests described would be likely to show up any variations due to boundary layer phenomena.

The variations in the α of the first flat plate are within the limits of definition claimed on p.13 of the report. The increase of α in the second flat plate may be due to bad siting as explained in MRP. 677. The increase in α of the M.O. conical-head thermometer is in accordance with theory and follows from the existence of a velocity gradient along the cone. Steps have been taken on later models to reduce the effects of this gradient. The variations in α of the Sangamo-Weston thermometer are believed to arise from insufficient thermal insulation between the sensitive element and the nose of the thermometer. The most astounding result of all is the effect of the trip wires on the α of the flat plate. The explanation given in the paper is the most plausible and agrees with observations recorded by Ackeret (Ric. Sci.20, Dec. 1950, 1926-7). No explanation other than structural damage can be given for the shift in the value of α of the first flat plate between the two series of flights.

The suggestion on p.3 to direct attention to reducing the coefficient is good practice where approximate temperatures are wanted but, in an aircraft whose specific purpose is to obtain accurate temperature observations, it is not thought that a thermometer carrying devices to reduce the α can be relied upon.

On p.8 5(b) the remarks about the position-error correction apply only if the methods of Charnley and Fleming are used. No correction for compressibility need be applied to the position-error if the methods laid down in MRP. 604 are followed.

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Discussion

The above results do not substantiate the previous finding that the speed correction coefficient of the M.O. flat plate thermometer decreases with height. It may be that this in fact does happen at greater heights and speeds than can be obtained by the Hastings aircraft but within these present limitations it is evident that this variation is of no practical importance as it is always masked by the scatter of the individual determinations.

The conical head thermometers showed a slight increase of the speed correction coefficient with height, a result which was anticipated in M.R.P. No. 677.

The experiment failed to demonstrate whether the trip wires or slotted elements eliminated any effects due to the position of changeover from laminar to turbulent flow on the thermometer surface as the M.O. flat plate thermometer with which they were compared did not show a significant change of its coefficient with height. It did demonstrate however that the coefficients vary considerably with the position of the element on the aircraft, and it seems that for work of good accuracy any installation would need a separate calibration before use.

The main result of the trip wires is to reduce the coefficient considerably. Cooling effects due to a bending of the streamlines of air flow have been noted in the literature and rather analogous effects are used in Vortex thermometers. It may be that development along the lines of reducing the coefficient itself may be more profitable for general service use than directing the effort into improving its constancy.

The accuracy of this work and its dependence on the accuracy of the other aircraft instruments is discussed in Part II of this report.

Table I. Flight results

1st Series

Type of Thermometer	Height in feet	No. of measure-ments	Mean α	Standard deviation	Smallest α measured	Greatest α measured
Standard M.O. flat plate	5000	20	1.73	0.12	1.53	1196
	21000	16	1.71	0.07	1.61	1.86
Sangamo-Weston conical head	5000	22	1.69	0.16	1.36	1.92
	21000	18	1.74	0.11	1.48	1.90
Flat plate without trip wires	5000	22	1.50	0.10	1.26	1.62
	21000	18	1.60	0.04	1.53	1.68
2nd Series						
Standard M.O. flat plate	5500	14	1.66	0.07	1.55	1.78
	21000	15	1.62	0.06	1.43	1.69
M.O. conical head	5500	14	1.83	0.08	1.67	1.96
	21000	15	1.87	0.07	1.81	2.04
Flat plate with trip wires	5500	14	1.16	0.07	1.04	1.24
	21000	15	1.14	0.03	1.06	1.17
Slotted flat plate with Venturi	5500	14	1.59	0.10	1.36	1.72
	21000	15	1.60	0.03	1.55	1.64

/Part II.

Part II. The Technique of Determining the Speed Correction Coefficients of Aircraft Thermometers

1. Definition of speed correction coefficient and its standard method of determination

On p.15 of M.O. 470 (5) the correction ΔT to be subtracted from the indicated dry-bulb temperature T_i is given by

$$\Delta T = a \left\{ \frac{V}{100} \right\}^2 \qquad (1)$$

where V is the true air speed and a is the speed correction coefficient. The recommended method of determining a is to fly in suitable conditions at a constant pressure level taking readings of indicated temperatures at speeds V_1, V_2, V_3, V_4, V_3, V_2, V_1 in order, where V_1, V_4 are minimum and maximum aircraft speeds respectively. a is then given by the slope of the best straight line drawn through values of indicated temperature T_i, plotted against $(V/100)^2$.

The value of true airspeed V is in each case obtained from the equivalent airspeed V_i by the equation:-

$$\left(\frac{V}{V_i}\right)^2 = 1.95 \frac{T + 459}{P} \qquad (2)$$

where T, P, are the ambient temperature in degrees Fahrenheit and pressure in millibars respectively and V_i is the reading of the air speed indicator with various corrections applied. These corrections increase in importance with speed and altitude and are discussed below.

It is also necessary to apply corrections to the altimeter readings before they can be used in equation (2) and these corrections are also discussed in a subsequent paragraph.

2. The accuracy required in the value of the speed correction coefficient

In the work described in Part I of this report a was found to be about 1.7 when the temperature was measured in degrees Fahrenheit and the airspeed in knots. The value of $\Delta T\,^{\circ}F$ and the error in ΔT if a is 0.1 in error are given for various airspeeds in Table II.

Table II

Some values of speed corrections and their errors at various airspeeds.

Airspeed V Knots	Correction $\Delta T\,^{\circ}F$	Error in $\Delta T\,^{\circ}F$
100	1.7	0.1
200	6.8	0.4
300	15.3	0.9
400	27.2	1.6
500	42.5	2.5
600	61.2	3.6

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It appears from this Table and the results of Part I that errors of 3.5°F or more may arise in temperature readings from fast aircraft due to uncertainties in the value of the speed correction coefficient. In the relatively slow Hastings aircraft used by M.R.F. the error is normally between 0.1 and 0.3°F.

3. Computation technique when the speed range is small

In para. 1 the technique involves using a range of airspeeds say V_1 to V_4. As the available indicated speed range was only 120 to 180 knots it was considered better to concentrate the readings at the corrected lowest, V_L, and the highest, V_H, equivalent airspeeds with respective indicated temperatures T_L, T_H. It follows then from equations (1) and (2) that providing both high and low speed runs are made at the same ambient pressure P then:-

$$\alpha = \frac{(T_H - T_L)\,P}{1.95\left\{\left(\frac{V_H}{100}\right)^2\left(T_L + 459\right) - \left(\frac{V_L}{100}\right)^2\left(T_H + 459\right)\right\}} \qquad (3)$$

$$(T + 459) = \frac{\left(\frac{V_H}{100}\right)^2\left(T_L + 459\right) - \left(\frac{V_L}{100}\right)^2\left(T_H + 459\right)}{\left(\frac{V_H}{100}\right)^2 - \left(\frac{V_L}{100}\right)^2} \qquad (4)\ .$$

For a small speed range this technique has statistical advantages and also simplifies the computation. It does however assume that equation (1) is correct. For large speed ranges it may be possible to detect deviations from this equation and then a range of speeds would have to be traversed.

4. The measurement of temperature

Care must be taken to provide the thermometer with a good exposure in a position under the wing or under the nose of the aircraft. All flying should be carried out without the sun's radiation falling directly on the element. The thermometer is calibrated in still air in the laboratory before use.

The problem is then to find a representative mean temperature for the same sample of air at the different aircraft speeds. This is complicated by (a) small scale inhomogeneities in the air mass (b) variation of mean temperature with time and (c) variation of mean temperature with distance. These are now considered separately:-

(a) Very small scale inhomogeneities of the type described in M.R.P. No. 658 (1) will be averaged by the lag effects of most types of aircraft thermometers. Those of the types described in M.R.P. No. 376 (1) however can only be minimised by flying for at least 3 to 5 minutes on each run i.e. up to 20 air miles and taking readings at least every 10 sec. In addition each run should be made as accurately as possible between two fixed air positions. High speed runs will then be of shorter duration than low speed runs.

(b) The change of mean temperature with distance is to a large extent covered by flying on reciprocal bearings between the two air

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positions. It may be some advantage to arrange the aircraft's course to be approximately along the expected direction of the isotherms at the level concerned but in practice this often conflicts with other considerations and is rarely carried out.

(c) Advective change of temperature is also covered by using air positions as above. Other possible changes of mean temperature with time will be minimised by keeping the period of each determination small. To examine the importance of this effect a small subsidiary investigation was carried out on the changes of temperature measured by radiosonde at Larkhill between 0900 and 1500 hours during the period Jan. 1950 to Sept. 1951 with the following result.

Table III

Mean temperature changes (neglecting sign) 0900-1500 hours at 850 and 450 mb at Larkhill.

Level mb	Average temp. change °F	Maximum temp. change °F
850	2.5	16
450	3.1	19

It thus appears that at least 0.5°F changes are to be expected in an hour and up to 3°F may easily be possible. A large proportion of these are advective but it seems that a change of 0.5 to 1°F due to dynamic and radiation effects is quite possible.

The measured changes due to the speed range are about 3°F at 5000 feet and 6°F at 21000 feet. Hence it is inadvisable to spend more than 15 to 30 minutes on a single experiment.

Another consideration which is discussed in greater detail below is the effect of varying altitude on the temperature readings. A lapse rate of 0.5°F in 100 feet is common and increases of greater magnitude are found in inversions.

5. The measurement of height and airspeed

(i) The altimeter and airspeed indicator are standard aircraft instruments operated by the air pressure in the pitot and static sources. The instruments themselves are calibrated in the laboratory against known pressures to determine their instrumental errors but a knowledge of the behaviour of the pitot and static sources requires a calibration of the aircraft itself.

The principal corrections which then arise in use are:-

(a) Calibration compressibility correction to the airspeed indicator readings.

(b) Corrections for position errors. Of these the static position error which affects both the height and airspeed readings is the more important.

At high speeds the static position error is varied by compressibility effects.

(ii) The calibration compressibility error arises from the fact that the airspeed indicator is calibrated as above for surface conditions only

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and at greater heights deviations from this calibration take place. A short Table is given below showing the magnitude of this error.

Table IV

Some calibration compressibility errors (knots)

Indicated airspeed (knots)	Height in feet 5,000	10,000	20,000	30,000	40,000
120	-0.1	-0.2	-0.5	-1.1	-2.1
180	-0.5	-0.7	-1.8	-3.7	-6.7
300	-1.7	-3.3	-8.2	-15.3	-

Corrections were made for these errors in the work described in Part I of this report.

(iii) Static position errors are due to the static source of the aircraft not always registering correct static pressure and giving different values at different airspeeds and heights. Correction should be made to both airspeed and height readings for this error. Hence the recommended method of measuring speed correction coefficients in Ref. 3 is to predetermine the height correction to the altimeter reading at the various speeds at which the experiment is to be made and then arrange the flight plan so that all the speed runs are made at constant pressure height. Corrections are then also applied to the airspeed readings. Unless this is done the actual height of the aircraft will vary with the aircraft speed and the results of the experiment will be in error by an amount depending on the temperature lapse rate.

The Hastings aircraft used in this work was calibrated for position errors just above runway height by comparing the readings of the aircraft instruments with surface photographic determinations of the true height of the aircraft. The errors at other altitudes were then determined theoretically by the methods given in Ref. 2 in which the assumption is made that the static pressure varies with the Mach number according to a relation given by Glauert. This relation at present is considered the most satisfactory and can be used confidently within the operating conditions of the Hastings aircraft. Some values for the corrections determined for the position errors of this aircraft are given in Table V. Between 100 and 130 knots I.A.S. this aircraft is flown with 40° flaps and "clean" at greater speeds.

Table V

Some height corrections Δh and speed corrections ΔV for position errors.

Height feet	Speed knots	120		180		220	
		ΔV knots	Δh feet	ΔV knots	Δh feet	ΔV knots	Δh feet
5,000		-1	-14	-1	-42	-3	-95
10,000		-1	-17	-2	-49	-4	-110
20,000		-2	-23	-3	-69	-6	-156
30,000		-3	-35	-4	-103	-8	-234

/(iv)

(iv) It is possible however to ignore the effects of position errors and determine the speed correction coefficient accurately provided that the lapse rate throughout all the runs everywhere is approximately the wet-adiabatic. Under these conditions it so happens that the effect of position error on altitude opposes its effect on speed. It can be shown that when the fraction of full kinetic heating attained by the thermometer is the same fraction as the actual lapse rate is of the dry adiabatic lapse rate, then the two effects cancel. In practice both these fractions are about 0.7 when the lapse rate is wet-adiabatic. The work described in Part I and also that described in M.R.P. No. 527 was carried out as far as possible in these conditions and position error effects were then disregarded.

It should be emphasised however that under isothermal and inversion conditions large errors will be introduced by neglecting position errors in this way.

(v) In a large aircraft where there are several instrument positions a variation occurs between them and it is necessary always to use the same position in this work. These installation errors were examined in flight where four 5 minute runs were made at about 150 knots I.A.S. at 5000 feet and 21000 feet with three sets of instruments being read simultaneously every 10 seconds. The results are given in Table VI.

Table VI

Variation of height and airspeed readings in different aircraft positions.

	2nd Pilot's Instruments		Navigator's Instruments		Engineer's Instruments	
	I.A.S. knots	Height feet.	I.A.S. knots	Height feet.	I.A.S. knots	Height feet.
Run No. 1						
Mean	151.1	5011	149.3	4997	149.9	4963
Standard Deviation	1.3	7.9.	1.6	10.1	1.0	9.2
Run No. 2						
Mean	151.0	5010	150.0	4994	149.7	4966
Standard Deviation	1.0	9.5	1.1	10.5	0.9	11.9
Run No. 3						
Mean	151.5	20915	149.3	20957	149.9	20996
Standard Deviation	1.1	11.2	1.6	14.4	0.9	14.6
Run No. 4						
Mean	150.6	20908	149.3	20948	149.4	20997
Standard Deviation	1.9	14.1	2.2	20.4	2.1	11.4

It appears that variations of 20 to 40 feet in heights at 5000 feet and 80 to 100 feet at 21000 feet may easily be produced by reading different altimeters in the aircraft. Moreover different altimeters may read higher at different altitudes. The uncertainty in mean speed is between 1 and 2 knots.

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The effect of systematic temperature and pressure differences introduced by flying the high and low speed runs at different levels

If the variation of temperature with altitude is $\partial T/\partial P$ ^{o}F per millibar and one run is flown at a pressure level P_1 and the other at a pressure level P_2, such that $P_1 - P_2 = \delta P$ the effective ambient temperature for one run will be T ^{o}F and for the other $T+\delta T$ ^{o}F.

To a good approximation equation (3) will then become:-

$$\alpha = \frac{T_H - T_L\left\{1 + \frac{\delta T}{T}\right)}{\frac{1.95}{100^2}\left[\frac{V_H^2}{P_2}\left(T_L + 459\right)\left\{1 + \frac{\delta T}{T}\right) - \frac{V_L^2}{P_1}\left(T_H + 459\right)\right]} \qquad (5)$$

P_1 and P_2 will of course be readily available from the altimeter readings, but in order to obtain the value of δT it is advisable always to measure the lapse rate at the relevant altitude preferably before and after the experiment.

In order to decide whether δT or δP can be ignored equations (6) below can be used. If $\delta\alpha_T$ is the error in α due to δT and $\delta\alpha_P$ is the error due to δP when equation (3) is used then:-

$$\left.\begin{aligned} \frac{\delta\alpha_T}{\alpha} &\doteq \frac{\delta T}{T_H - T_L} \\ \frac{\delta\alpha_P}{\alpha} &\doteq \frac{\delta P}{P} \end{aligned}\right\} \qquad (6).$$

In practice $\delta\alpha_P$ is usually negligible and $\delta\alpha_T$ is small so that $P_1 = P_2 = P$ and δT can be applied directly as a correction to T_L which can be used in equation (3).

The effect of random errors in temperatures, speed and height readings on the computed value of the speed correction coefficient

If the respective random errors in T_L, T_H, V_H, V_L and P are r_1, r_2, r_3, r_4 and r_5 respectively, then there will be an error in α which is given by:-

$$r_\alpha^2 = \left(\frac{\partial\alpha}{\partial T_L}\right)^2 r_1^2 + \left(\frac{\partial\alpha}{\partial T_H}\right)^2 r_2^2 + \left(\frac{\partial\alpha}{\partial V_H}\right)^2 r_3^2 + \left(\frac{\partial\alpha}{\partial V_L}\right)^2 r_4^2 + \left(\frac{\partial\alpha}{\partial P}\right)^2 r_5^2 \qquad (7).$$

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By performing the differentiations on equation (3) and taking typical values of the random errors it is possible to estimate the relative effect of these various random errors on r_α .

In the following chosen example:-

Height	P	T	V_H	V_L	r_1	r_2	r_3	r_4	r_5
feet	mb	°F	knots	knots	°F	°F	knots	knots	mb
5000	843	41	180	120	0.2	0.2	1.5	1.5	0.5

r_α was computed to be approximately 0.15, the main contribution being due to temperature errors. Speed errors alone would cause 0.06 and altitude errors 0.002.

A similar example worked out for typical conditions at 21000 feet showed that compared to 5000 feet the effect of random temperature errors is nearly halved, that of pressure errors nearly doubled while that of speed errors was about the same. Hence successive determinations of α are likely to be more consistent at the higher levels and this in fact is shown in the results of Part I of this report.

It appears incidentally from a consideration of the components above that random errors in speed and height readings become more important in the high speed run than in the low speed run.

The flying necessary to obtain a given accuracy in a speed correction coefficient

If a single determination of the speed correction coefficient has a probable error of say 0.15, the number of determinations required to obtain a probable error of 0.05 will be nine and of 0.01 two hundred and twenty five. This latter is prohibitive and 0.05 is probably the highest accuracy obtainable in practice for a calibrated aircraft.

Discussion

In addition to the errors discussed in the preceding paragraphs other inconsistencies always appear in the practical measurement of temperature from aircraft. Turbulence may affect the readings obtained from a pitot static system (4) and also the performance of the thermometer itself (M.R.P. No. 677 and 744). A "pitot position error" may also be produced due to small angles of pitch and yaw. In general an apparently random error of about 0.3°F usually appears in all attempts to measure temperature, e.g. in sequences of the same average temperature over say 5 minute runs, and this may be due to any or all of the above causes rather than a small change in the mean air temperature.

It appears therefore that it is not likely that the air temperature measured even from a research aircraft will have an accuracy better than about 0.5°F. In view however of the inhomogeneity of the atmosphere this is usually satisfactory for most practical purposes. However in a fast aircraft which has not been specially calibrated a single determination of air temperature may easily be up to 5°F in error.

It is considered that any further experimental work on this subject should now await the availability of fast aircraft with a wide speed range at great heights. It may become possible with this aircraft to

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detect with certainty whether the speed correction coefficients of these aircraft thermometers do in fact vary with height as the importance of the random errors should then decrease. The considerations outlined above should be taken into full account when this work is done, and in particular great attention should be paid to position error effects as these increase considerably with speed and with altitude.

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